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Art. VII.—*Tertiary Dykes and Volcanic Necks of South Gippsland, Victoria.*

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(With Plate VII.)

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Introduction.

The Geological Survey of Victoria, over a period of years from 1890 to 1920, published a number of reports, by Stirling (1892), Kitson (1903, 1917), and Ferguson (1909), in which were included detailed accounts of the geology of the areas covered by a series of Quarter Sheets—Nos. 67.S.E., 67.N.E. 75.SW., 76.SW, and 76.NW. (unpublished). In the course of this field work, an extensive collection was made from the dykes and volcanic necks herein described, to which later workers have added. The specimens were sectioned, and five analyses were prepared in the Survey Laboratory.

At the time of the author's departure for England to take up an 1851 exhibition, this collection was put at his disposal through the generosity of the present Director of the Geological Survey of Victoria, Mr. W. Baragwanath, together with a number of unsliced specimens. These latter have been sectioned in the Geology Department of Imperial College, and six further analyses have been completed.

The general geological map of South Gippsland, published in the Report of the Secretary for Mines, Victoria, for the year 1917, has been used as the basis of the appended sketch map. Locations of dykes and plugs were added from quarter-sheets, parish plans, and other records. The positions of the fault lines are based upon information supplied by the Geological Survey of Victoria.

The probable extent and strength of the dyke swarm can only be conjectured, owing to the limitation of exposures by the deep surface soils and vegetable accumulations of the gullies, by the dense undergrowth and forest that covers most of the hills, and by the burying of the dykes in the down-faulted blocks by later Tertiary sands. Bore records show that the dykes occur, to unknown extent, in these down-thrown areas.

General Features of the Dykes and Volcanic Necks.

The Dykes.

These are composed of a suite of analcite-olivine-dolerites (crinanites), olivine-basalts, and monchiquites. They show a strong north-westerly trend, with indications of a minor group striking north-easterly to easterly, both groups being contemporaneous.

They are best exposed in the strip of Jurassic country parallel with the coast line from Kilcunda to Cape Paterson, either along the shore-line, or on the deforested hills. Describing this area, Ferguson (1909, p. 8), states:—

"All the dykes observed were in the Jurassic rocks and were basaltic, though their texture varies . . . so that they appear to range from fine-grained basalts to gabbros. They vary in width from a few inches to two chains. . . . and range up to 20 chains in length."

Stirling (1890, 1892), examined dykes in the Parishes of Jeetho, Jeetho West, Poowong, and Korumburra. These dykes also intruded and indurated the Jurassic country rocks, and all but one showed the north-westerly strike. The exception was a large doleritic dyke which crosses the railway cutting in the Korumburra township reserve, and trends north-easterly. A small basaltic dyke just west of Outtrim township has an east-west strike; and a large doleritc dyke met with in the workings at Turton's Creek strikes north-east; but all other dykes whose strikes have been recorded have the north-west strike. They have been affected by both major and minor faults, and the Bena and Korumburra dykes rise through anticlinal structures in the Jurassic sediments.

The dykes described by Stirling are generally larger than those in the Kilcunda area, the largest being the Cruikston Dyke (allotments 21, 23, Parish of Poowong), which is about 16 chains across, and has a coarse gabbroic texture. It thins out to the south-east. The Cheviot Neck (Parish of Jumbunna East) is similar.

Felsitic Dykes.

Felsitic dykes have been recorded in various parts of the area (Murray, 1876; Stirling, 1892). These intrude the Jurassic sediments, and were locally faulted during the intrusion of the dolerite dykes. They are commonly much decomposed, but fresh samples show them to be trachyandesites. It seems probable that they represent an acid differentiate of the "crinanitic" suite.

The Volcanic Necks.

The volcanic necks of South Gippsland are divisible into two main groups:—A group of eight, all of a basic, and generally clastic, character, outcropping along the coast from Cape Paterson to Anderson's Inlet: and another group of about ten, which are more basaltic, and generally free from clastics, occurring north-west of the Kongwak Fault, in the Parish of Jumbunna East. Isolated plugs occur farther to the north, e.g., the olivine-nephelinite plug near Drouin West.

The largest of the four necks at Cape Paterson has a three-quarter acre pear-shaped outcrop, and intrudes Jurassic sediments, which are indurated for several feet from the contact. The greater part of the plug is occupied by a dense blue-black tuff, composed of fragments of basic igneous rocks. It is traversed by small irregular dykes, and in places roughly columnar monchiquite is found. This contains scattered crystals of felspar, and large masses of olivine, much of which is decomposed, up to 2 feet across. Inclusions of Jurassic material are numerous.

The four volcanic necks at Anderson's Inlet (Kitson, 1903), differ from those in the other parts of the area by being composed almost entirely of clastic material. Blocks of two types of basalt are found in the agglomerates—a dark dense rock (monchiquite) with patches of olivine, and a very vesicular grey basalt. The neck near the mouth of Screw Creek is rimmed with a narrow shell of finely vesicular scoriaceous mud-basalt, which shows laminations parallel with the wall. It contains some hard blocks of basalt, but is mainly composed of an agglomerate of blocks of decomposed basalt, Jurassic sediments, tuff and lapilli, and a material that resembles volcanic mud. The largest neck of the group has a visible extent of outcrop of 12 chains by 8 chains before it passes under the sea, or into the mangrove swamps.

The group of volcanic necks north-west of the Kongwak Fault have been described by Kitson (1917) :—" In size the necks vary from a few square feet to 53 acres. They are ranged roughly along certain lines, and occur either singly, or in small groups. The rocks forming the necks are either coarse-grained or very fine-grained. The coarse-grained type (dolerites) occurs at the Cheviot Neck, and at Pollock's Hill (allotment 54, Parish of Jumbunna East). There are several similar occurrences to the north and north-east.

The fine-grained type (monchiquite) . . . may contain scattered crystals of felspar, hornblende, black mica, olivine, and pieces of glass. The porphyritic type occurs in the four largest necks (Moyarra, Wilson's Knob, the adjoining neck, and the Wolonga Neck). The cryptocrystalline rock occurs at Thompson's Hill, Krowera, and in one of the group of necks of allotment 54, Parish of Jumbunna."

Tufaceous basaltic outcrops, possibly necks, occur in allotment 30A, 37, 41A, and 23C of Kongwak, and in allotment 31 of Kirrak. Ferguson also regards as possible necks the three outcrops in allotments 26A and 94C of Woolamai, and 9 of Kirrak.

Petrography.

Olivine-Nephelinite.

A single plug of this rock has been found in South Gippsland; and the only other occurrence known in Victoria is a plug associated with monchiquite dykes, found near Greendale. It is not known for certain that the nephelinite belongs to the association to be described in the following pages, but it is of the same age, and many features suggest that it should be included. The Greendale nephelinite has more distinct monchiquitic features.

The olivine-nephelinite, which has been described by Mahony (1931), is worked in a quarry in allotment 91, Parish of Drouin West, and from the map appears to penetrate, and so post-date the Older Basalts. Actually it is surrounded by basaltic soils, and no definite relations are to be observed, but it has been proved to be a plug by boring.

Microscopically it is a holocrystalline, panidiomorphic rock, consisting of nepheline, augite, olivine, and iron-ore; felspar is absent. Nepheline, in limpid and colourless crystals, some of which are 0.25 mm. wide, and almost microporphyritic, forms about one-third of the rock. Pyroxene is the next most abundant mineral, forming colourless to greenish, and non-pleochroic prisms, about 0.08 mm. long, in felted aggregates between the nepheline crystals. Olivine is microporphyritic in fairly abundant idiomorphic crystals from 0.5 to 1.5 mm. across; it is partially altered to serpentine, and is then marked along the rim by a strong irregular border of iron-ore crystals, thrown down during the serpentinization. Abundant cubes of titaniferous iron-ore and rods of apatite are scattered uniformly throughout the rock. Elongated zeolites are present, probably of natrolite.

The Greendale nephelinite approaches closer to a monchiquite, having less nepheline, and rather more augite, both in the ground mass and as microphenocrysts—a brown augite, with a narrow rim of titanaugite. The augite crystals are idiomorphic and zoned, with their cores rich in iron-ore inclusions ("spongy"), or the core may be greenish, due to the presence of the aegirine molecule. The analyses (Table 1, Nos. 1 and 2), show the difference in amount of nepheline and pyroxene in the higher Na_2O and lower CaO of the Drouin rock; and it is to be noted that while the TiO_2 content of the two rocks is similar, only one of them reflects its presence in possessing titanaugite.

Monchiquites.

True monchiquites have been collected from some twelve localities within the area, including both dykes and volcanic necks; and though the latter might be designated limburgites appropriately, it has been thought simpler to describe all the very similar specimens by the same name. The close similarity between these rocks and the monchiquite dykes of the Bendigo gold-field makes the term monchiquite the more suitable. No analysis of the typical monchiquite has been made on this account, but a Bendigo analysis is quoted (Table I., No. 3), to give the approximate composition.

In hand specimens the rocks are generally dense and bluish-black in colour, with occasional microphenocrysts of greenish olivine, and more numerous small white vesicles.

Under the microscope the microphenocrysts of olivine are seen to be thoroughly serpentinized. They average about 0.3 mm. across, and retain their idiomorphic outline. Xenocrysts of fresh olivine, showing strong reaction rims or corrosion, are occasionally observed. These are as large as 3 mm. in diameter, and irregularly concentrated.

These phenocrysts are set in a uniformly fine ground-mass, which consists of idiomorphic prisms of augite, a little altered olivine, iron-ore, some biotite, hornblende, and a quantity of glassy material. Patchiness, due to local concentration of glass, is a feature of the groundmass, just as in the Bendigo dykes (Stillwell, 1912). Rare grains of picotite are present.

The augite shows zoning—a diopsidic core with a titanaugite rim—and is markedly idiomorphic. The titanaugite is pleochroic, generally faintly, with X = yellowish, Y = reddish-violet, Z = yellowish. The iron-ore is equally idiomorphic, in octahedra, smaller in size than the augite prisms with which it is associated. Intersertal between these is the glassy material, which is generally clear and colourless, but turns yellow and deposits trichytes of iron-ore during devitrification. It is always an important constituent.

Occasional scales of biotite and hornblende occur in association with lighter-coloured patches of the groundmass, and with certain of the vesicles. These scales may be shreds with no structure, or laths up to 0.1 mm. long, showing strong pleochroism from brown to straw-yellow, and provide a close parallel with the biotite and hornblende flakes of the Bendigo dykes. Reaction between the iron-ore and the apparently felspathic glassy residuum seems to contribute to their formation.

No felspar is observed in the typical sections, but in one or two with basaltic tendencies a few fine laths or microliths of labradorite are dispersed through the groundmass.

Amygdales may be very abundant, and may contain (*a*) fibrous natrolite, (*b*) chlorite and aragonite, or (*c*) an isotropic material similar to the glassy base. The last (*c*) is often surrounded by dark zones, due to the abundant development of skeletal iron-ore, together with biotite and hornblende laths. Crystals of the latter minerals are largest at the outer edge, and there show tendencies towards radial orientation of their long axes about the amygdale. Nearer the amygdale the skeletal iron-ore is concentrated, and the biotite and hornblende diminish to mere scraps. Some of these amygdales contain ragged cores of calcite within the glass, and in the calcite are small isotropic cubes of analcite (?). In some cases these amygdales extend as short veins into the rock.

Cape Paterson Variety.

The rock from the largest neck at Cape Paterson contains microphenocrysts of both olivine and augite, set in a glassy base which is rich in iron-ore. The olivine is generally fresh, and is margined by well-marked reaction rims of brown to purple-brown augite. Like the olivine, the augite microphenocrysts are idiomorphic. They consist of a colourless core of diopsidic material, with an outer zone of purplish-brown, pleochroic titanaugite. Some of the crystals exhibit twinning parallel to (100), with thin lamellae separating the principal parts of the twin.

Picotite is present in small grains, included within olivines, and small zeolites are frequent. The analysis (Table I., No. 4) shows the rock to be richer in magnesia, and poorer in titania than the normal type, and agrees well with a microscopically similar rock (Analysis No. 5) from Moorabool East, which is also associated with normal monchiquite dykes.

Anderson's Inlet Variety.

The specimen from Townsend Bluff (Neck No. 1, of Kitson) is richer in augite than that at Cape Paterson, and contains microliths of plagioclase. The augites show three zones; the innermost zone is occasionally green, and pleochroic to yellow, indicating the earlier development of the aegirine molecule, but more commonly both the inner zones are colourless, the second being very narrow. The rim is of brownish-purple titanaugite, which is pleochroic with X = yellow, Y = brownish-purple, Z = faint yellow. The central zone may contain inclusions of more or less altered olivine. The groundmass, apart from the plagioclase, is similar to that of the Cape Paterson rock.

Xenoliths of Dunite.

Masses of olivine, up to 2 feet in diameter, have been observed in the monchiquitic volcanic necks. These must represent either segregations of the olivine from the magma of the monchiquite, or a dunitic phase within the magma chamber, through which, or from which, the monchiquitic material was forced.

Such a xenolith, found in the large Cape Paterson neck, consists almost entirely of olivine and picotite. The edges of the olivine crystals are sometimes deeply iron-stained, and almost opaque. The olivine itself is colourless, and contains less than 12 per cent. of FeO. Individual grains reach 1.5 mm. across, but the average is 0.5 mm. They are allotriomorphic, and the picotite is either included within, or caught up between the crystals. The approximate composition is:—Picotite 5 per cent., olivine 70 per cent., and opaque iron-stains about 25 per cent.

Monchiquite-Basalts.

The rocks of this group are about as equally developed as the true monchiquites, and include most of the smaller plugs of the Jumbunna East group. They grade by increase of plagioclase into olivine-basalts, and by decrease of plagioclase into true monchiquites.

In the hand specimen they are not to be differentiated from the monchiquites. They weather to a greyish rock with a fine hackly fracture. Analyses have been made from the Moyarra Neck, in the south-west of allotment 55, Parish of Jumbunna East, and from Glanfield's cultivation paddock, near Kilcunda (Table 1, Analyses Nos. 6 and 5 respectively).

These rocks differ from the monchiquites in that the olivine crystals are usually rounded by resorption. The groundmass is equally uniform, but coarser, and contains a characteristic, though variable, amount of plagioclase, which may be in the form of minute microliths, or as numerous laths of the composition $Ab_{50}An_{50}$. The glassy base appears to be related to the felspar, and is rich in trichytes of iron-ore. Analcite may be present, and is accompanied by shreds of biotite. Fine needles of apatite are abundant, and rare grains of picotite are included in the olivine crystals. The zeolites parallel those of the monchiquites.

This gradation of monchiquite into olivine-basalt is similar to that described by Stillwell (1912) for the Bendigo monchiquites.

Anorthoclase Crystals.

The large crystals of felspar found in these rocks (Kitson, 1917) are of a composition approaching $Or_{23}Ab_{68}An_{9}$, from a poor analysis (Mahony, 1928).

Olivine-Analcite-Basalts.

These may be described under two groups.

Group A.—Basaltic Dykes with Titaniferous Augite.

Several of the necks, and a number of the dykes, fall in this group. The typical analysis from Callanan's Hill (Table 1, No. 8) shows very little difference in composition from those of the monchiquite-basalts; but there is a marked contrast in their microscopical appearance, owing to the much coarser and less uniform groundmass of the olivine-basalt. These average about the texture of a medium-grained intergranular basalt, and grade towards the analcite-olivine-dolerites with increase of grain size. The difference is accentuated by the increased amount of plagioclase present in the sections.

The idiomorphic or corroded microphenocrysts of olivine average about 0.4 mm in diameter, and are serpentinized to varying degrees. They are set in an intergranular, sometimes partially ophitic groundmass, in which the felspar laths tend towards parallel orientation. The augite of the groundmass equals the plagioclase in quantity, and is idiomorphic, or in small plates of reddish-violet colour, with weak pleochroism to a faint yellow, the violet colour often being limited to the rim zone about a diopsidic core. The iron-ore is coarser than in the monchiquite-basalts, and less evenly distributed. Analcite occurs abundantly intersertal to the other minerals, or in zeolitic patches, and is both turbid and clear. A little colourless felspar, possibly orthoclase, shreds of biotite and needles of apatite accompany it.

Group B.—Basaltic Dykes Poor in Analcite and with no Titanaugite.

Analysis No. 9 (Table 1) shows this variety to be richer in Al_2O_3 and poorer in MgO than the group preceding. This is reflected in an increase in plagioclase at the expense of olivine. The augite is generally colourless, but may show a faint violet colouration under high magnification. There is also a trace of the aegirine molecule where analcite appears, but the amount of the latter discernible is very small. The titania has gone to the iron-ore crystals, which are rod-like and skeletal. Interstitial orthoclase is present, and in some cases the plagioclase laths are larger than usual, developing microphenocrystic habit.

Analcite-Olivine-Dolerite.

Analcite-olivine-dolerites (crinanitic dolerites) are the most widespread type among the dykes, and they also form the larger volcanic necks, e.g., Cheviot's Hill and Pollock's Hill. With a decrease of olivine and an increase of analcite the latter outcrops would become teschenites.

The hand-specimens have a coarsely crystalline grey to greenish appearance, suggestive of a fine-grained gabbro, with individual felspars and augites as large as 5 mm. in length.

The typical rock consists of olivine, augite, labradorite, and analcite, with some alkali felspar, iron-ore, biotite, in some cases a little aegirine, and rare scraps of barkevikite. Natrolite and analcite form zeolitic patches, and the rock is pierced with abundant coarse rods of apatite. Ophitic texture is prominent, but may be subdued by the idiomorphic tendencies of the augite.

The olivine forms unaltered, but corroded, crystals up to 3 mm. across. Being the first mineral to crystallize, apart from the apatite, it is often enclosed by small unorientated augite individuals, or by poecilitic augite plates.

The augite is more abundant than the olivine, and is strongly zoned, the inner zone being colourless or faintly yellow, and the outer a pleochroic pinkish-violet, with X = faint yellow, Y = pinkish-violet, Z = faint yellow. It shows twinning parallel to (100), with thin lamellae separating the principal parts. In some dykes the crystals are strongly idiomorphic, but more generally the augite forms plates from 2 to 3 mm. across, which may be fractured by differential movements. The colour varies locally, and in some examples the augite is colourless or only very faintly violet.

Analcite appears in varying quantities, reaching a maximum of about 15 per cent. by volume in the Doomburrim and Cruikston dykes. It occurs interstitially, as clear or turbid patches, between the felspar laths, and when in contact with the violet augite, it reacts with the latter to form a green pleochroic pyroxene, of a composition varying between aegirine-augite and aegirine, depending on the degree to which the Na_2O has been incorporated in the pyroxene. Small idiomorphic crystals of aegirine, pleochroic from green to yellow, are found within patches of analcite. Aegirine develops only where augite is in contact with analcite; the rims cease where the augite has been sheltered by a plagioclase lath or an olivine crystal. Rare scraps of barkevikite are found within the analcite areas. The analcite has "patterned" the plagioclase, but the latter is too fresh to have been the source of the soda in the analcite; it must be regarded, therefore, as pyrogenetic or deuteric in origin.

Two types of felspar are present:—(*a*) laths of labradorite, and (*b*) interstitial alkali felspar, which appears to be orthoclase (this would agree with the high percentages of K_2O shown by the analyses, Table 1, Nos. 10–13). The plagioclase laths in the coarser rocks are 3 mm. by 0.5 mm., but for the more average-grained types are between 1 and 2 mm. long. They are generally of labradorite composition—$Ab_{45}An_{55}$; but in some cases are more acid. Some show strong zoning, with a marginal zone of oligoclase, while in the Korumburra dyke the marginal zone is nearly as wide as the labradorite core, and is of albite-oligoclase. The felspars, like the augites, are fractured by differential movement.

The iron-ore occurs as irregular plates, up to 1 mm. in diameter, generally ophitic about plagioclase laths. A few inclusions of it are seen within the augites, but never within the olivine crystals. Associated with the iron-ore and the analcite is a small amount of biotite, which forms strongly pleochroic laths and scales, making partial or complete rims about the iron-ore crystals. The abundant apatite rods may be up to 2 mm. long.

The order of crystallization has been:—Apatite; olivine; iron-ore, augite, plagioclase; alkali felspar, analcite, biotite, aegirine, barkevikite, and natrolite.

Felsitic Dykes.

Only one specimen of the felsitic or "wackenitic" dykes of Stirling (1892) was sufficiently preserved for sectioning.

This rock, which intrudes the Jurassic sediments in the Outtrim cemetery, consists of microphenocrysts of acid andesine, $Ab_{65}An_{35}$, and long flakes of hornblende, set in a holocrystalline groundmass of slightly more acid plagioclase, orthoclase, a trace of quartz, shreds of hornblende and biotite, and a very little iron-ore. The felspar phenocrysts are idiomorphic, and show combined Carlsbad and albite twinning with strong zoning, and have a microscopic outer rim of orthoclase. The hornblende is a light green variety, idiomorphic in small crystals, but more commonly poorly structured, and apparently about to change over to biotite. Both sets of phenocrysts show sub-parallel orientation from flow movements.

The groundmass is granular to sub-trachytic, and formed of idiomorphic basic oligoclase $Ab_{70}An_{30}$, with intersertal orthoclase and quartz, shreds of biotite, and hornblende, and grains of iron-ore.

Reactions Observed.

The reactions observed to be taking place throughout the suite may be summarized as follows:—

1. Olivine → diopsidic augite → titanaugite → aegirine-augite → aegirine → barkevikite.
2. Ilmenite + analcite (or plagioclase) = biotite.
3. Ilmenite + analcite (or plagioclase) = hornblende.
4. Lime-soda plagioclase → soda lime plagioclase.
5. Olivine = serpentine + magnetite.

The serpentinization has occurred before consolidation. Idiomorphic olivine microphenocrysts in the monchiquites are strongly, if not completely, serpentinized, but in some slides there are found, in addition, fresh corroded xenocrysts of this mineral; and in others, some fresh cores of olivine have been retained by the formation around them of a protecting rim of augite. In the doleritic rocks serpentinization of the olivine is a minor feature, and commonly absent. The water vapour has preferred combination with the analcite molecule.

Geochemistry and Differentiation.

The Analyses.

The table of analyses is most informative when considered in conjunction with the table of norms. While the CaO content does not vary greatly throughout the series, the normative anorthite content rises more or less progressively from the basic to the less basic rocks. This represents an increase in plagioclase and a corresponding decrease in pyroxene. Normative olivine decreases as the anorthite increases. Albite and nepheline, as individuals, fluctuate; but taken in combination, they show an increase parallel to that of the anorthite. The Na_2O content in the analyses reflects this; but among the dolerites the concentration of Na_2O shows marked local variation, according as to whether the individual dykes are rich or poor in analcite. The K_2O, by contrast, remains much steadier throughout, and is higher than is usual for crinanitic rocks, while the TiO_2 is low for them (a fact reflected in the pale colour of the titanaugite), and falls progressively from the nephelinite towards the dolerites.

ANALYSES.

—	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	—
SiO_2	41·13	42·39	40·92	41·95	43·12	44·71	45·73	47·15	45·12	47·70	49·30	47·56	46·76	SiO_2
Al_2O_3	15·74	16·17	11·34	12·50	12·65	15·40	15·17	20·48	15·60	17·76	16·36	16·79	22·85	Al_2O_3
Fe_2O_3	4·02	4·29	0·54	4·02	2·66	4·14	3·90	1·61	9·01	2·23	2·74	3·05	3·80	Fe_2O_3
FeO	7·71	5·79	12·96	9·38	8·49	7·64	7·66	9·33	7·21	8·25	8·58	8·71	5·83	FeO
MgO	7·98	7·66	7·78	12·76	14·86	10·83	9·03	4·61	9·01	6·50	6·43	6·30	4·32	MgO
CaO	10·48	11·57	9·28	8·48	10·49	9·00	8·97	8·13	8·04	9·37	8·55	8·57	8·05	CaO
Na_2O	5·56	4·26	3·27	2·82	2·43	2·75	3·21	3·64	3·52	3·34	3·41	4·96	5·30	Na_2O
K_2O	1·12	1·46	1·94	1·34	0·73	1·64	2·27	1·66	0·88	1·59	1·64	1·78	1·54	K_2O
H_2O+110	2·11	1·85	1·77	2·31	1·25	0·65	1·02	1·30	1·61	0·85	0·59	2·23	1·55	H_2O+110
H_2O-110	0·58	0·56	0·64	1·15	0·53	1·00	0·51	0·32	..	0·27	0·88	..	..	H_2O-110
CO_2	Nil	Nil	2·82	0·87	0·28	0·60	tr.	Nil	..	tr.	Nil	..	..	CO_2
TiO_2	2·34	2·13	6·57	1·32	1·55	0·89	1·96	1·46	..	1·02	1·00	..	..	TiO_2
P_2O_5	0·54	1·16	0·51	0·48	0·61	0·60	0·60	0·38	..	0·51	0·40	..	Tr.	P_2O_5
MnO	0·14	0·23	0·13	0·33	0·20	0·27	0·18	0·25	tr.	0·24	0·25	tr.	..	MnO
Li_2O	tr.	..	..	..	..	..	..	..	..	..	..	..	..	Li_2O
Cl	Nil	0·11	..	0·08	0·01	tr.	0·03	0·02	Nil	0·03	Nil	..	..	Cl
S	Nil	0·13	..	Nil	Nil	Nil	tr.	tr.	Nil	0·02	Nil	tr.	..	S
BaO	Nil	0·01	..	Nil	0·06	Nil	0·01	tr.	..	0·03	Nil	..	..	BaO
Total	99·45	99·70†*	100·47	99·75*	99·92	100·11	100·33*	100·38*	100·00	99·69*	100·13	99·95	100·00	Total

† NiO nil, Cr_2O_3 0·03, V_2O_3 0·01, SrO tr.

* Corrected for Cl, S.

NORMS.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	
Q	..	..	..	..	..	..	..	..	..	..	..	..	..	Q
Or	6·64	8·62	11·46	7·90	4·34	9·68	13·37	5·19	9·79	9·68	9·45	10·55	9·15	Or
Ab	2·26	11·85	20·24	15·34	10·07	17·88	15·20	24·56	24·50	28·84	22·86	16·33	19·41	Ab
An	14·61	21·12	10·51	17·51	21·45	24·84	20·19	24·12	34·42	24·55	28·76	18·21	33·94	An
Ne	24·32	12·67	4·01	4·58	5·68	2·92	6·50	2·88	3·41	..	2·84	13·94	13·84	Ne
C	..	..	..	..	..	..	..	..	..	..	..	..	..	C
di	27·29	20·57	11·71	12·82	19·89	9·73	16·32	12·64	2·87	12·63	11·77	20·10	4·99	di
hy	..	..	..	..	..	..	..	..	..	0·19	..	..	..	hy
ol	10·23	8·68	19·25	26·97	27·77	21·70	17·25	15·93	17·58	16·03	16·43	14·16	11·62	ol
mg	5·83	6·22	0·79	5·84	3·85	6·00	5·65	13·06	2·34	3·97	3·24	4·42	5·51	mg
il	4·42	5·06	12·47	3·14	2·93	1·69	3·72	..	2·78	1·90	1·94	..	..	il
hm	..	..	..	..	..	..	..	..	..	..	..	..	..	hm.
ap	1·18	2·76	1·21	1·14	1·45	1·61	1·42	..	0·94	0·94	1·21	..	..	ap
cal	..	..	6·41	1·98	0·64	1·36	..	..	..	..	..	..	..	cal
pyr	..	0·24	..	..	..	..	..	..	..	..	..	..	..	pyr

Analyses:—

1. Olivine-nephelinite, plug in allot. 91, Parish of Drouin West. (F. F. Field.) Proc. Roy. Soc. Vict., 1931.
2. Olivine-nephelinite, plug, 8 chains S. of Greendale Hotel, Parish of Blackwood. (A. B. Edwards.)
3. Monchiquite dyke, Central Red, White, and Blue Mine, Bendigo. (F. Stillwell.) Proc. Roy. Soc. Vict., 1912.
4. Monchiquite pipe, Old Landing Place, Cape Paterson, Gippsland. (A B. Edwards.)
5. Monchiquite dyke. allotment 2, section VIII., Parish of Moorabool East, in Korweinguboora Creek. (A. B. Edwards.)
6. Monchiquite-basalt, Glanfield's Cultivation Paddock, Kilcunda, Parish of Woolamai. (A. B. Edwards.)
7. Monchiquite-basalt, Moyarra Neck, Parish of Jumbunna East. (A. B. Edwards.)
8. Olivine-analcite-basalt, Callanan's Hill, north end, Parish of Jumbunna. (Bayly, 1902—poor analysis.)
9. Olivine-basalt dyke, Logan's Paddock, Kilcunda, Parish of Woolamai. (A. B. Edwards.)
10. Olivine-analcite-dolerite, alkali-felspar type, Creek west of Gibson's allotment, Kilcunda, Parish of Woolamai. (A. B. Edwards.)
11. Olivine-analcite-dolerite, dyke opposite Cadd's smithy, Kilcunda, Parish of Woolamai. (A. B. Edwards.)
12. Analcite-olivine-dolerite, Cruikston dyke, allotment 21, Parish of Jeetho. (J. Dennant.) Prog. Rept. X., 1899.
13. Analcite-olivine-dolerite, Kilcunda-road State School, Parish of Jumbunna East. (Bayly, 1903.)

The Variation Diagram.

The variation diagrams (Fig. 1), plotted from analyses calculated to 100 per cent., free of water and calcium carbonate, place the rocks as follows, in the decreasing order of their silica percentage:—Analcite - olivine - dolerites; olivine - analcite - basalts; monchiquite-basalts; monchiquites; olivine-nephelinites. This arrangement is parallel with the decreasing order of grain size of the crystals (Fig. 2).

Three of the constituents give approximately straight-line graphs—K_2O, TiO_2, and P_2O_5, except for the TiO_2 of No. 3, the typical monchiquite. A different form of curve is necessary to fit the points for the other constituents. As the basic end of the series is approached, the stem of the curve splits along two divergent paths towards the monchiquite group and the nephelinite group respectively.

The divergence is most complete for Al_2O_3 and Na_2O; in the other three graphs one or other of the monchiquite points falls on the nephelinite curve.

In the acid region (the dolerites), three analyses (Nos. 9, 11, 13) fall above or below the curve. If arranged in the reverse order of their acidity—13, 9, 11—it is seen that a deficiency of iron and magnesia corresponds with an equally great excess of alumina, suggesting that excess sinking of olivine is the explanation of this divergence.

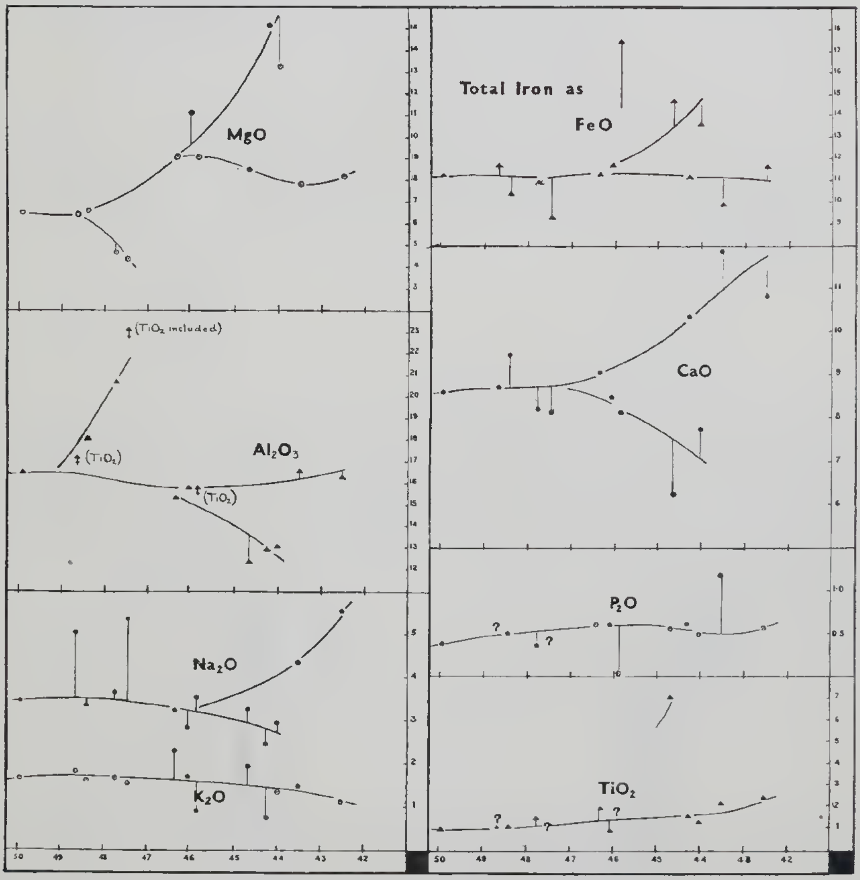

Fig. 1.—Variation Diagram.

The source of the high Na_2O in analyses 13 and 12 cannot be explained in this manner; but it is reflected in the rocks, which are especially rich in analcite. It suggests that the concentration of soda is independent of the concentration of the lime, and takes place locally. This suggests that the origin of the analcite might be deuteric (compare Daly, 1933, p. 398, in connexion with the late concentration of soda in the crinanite of the Shiant Isles).

The graphs throw little light upon the origin of the nephelinites, beyond demonstrating a number of points which they have in common with the monchiquites.

Differentiation.

No instance of one dyke rock intruding another type is known. The only direct evidence for age sequence is a xenolith of colourless augite ophitically intergrown with plagioclase (acid labradorite) found in one of the monchiquite necks at Anderson's Inlet. All the varieties occurs as dykes in close parallel associations, the dolerites being dominant, intruded contemporaneously, so that the differentiation, or much of it, must have occurred within a pre-extrusion magma chamber.

Assuming this, the rocks have been arranged in a column of increasing order of acidity, which should represent in some degree the state of differentiation and the temperature gradient of the magma immediately prior to the intrusion of the dykes. The table of specific gravities, where known, for this arrangement is:—

Dolerites	2.28–2.95
Basalts	2.68
Monchiquite-basalts	2.78
Monchiquites	2.80–2.99
Nephelinites	3.05

This, in itself, carries little weight as evidence.

Figure 2, drawn in conjunction with this assumption, illustrates the relative grain size of the constituent minerals. It is seen that olivine was phenocrystic throughout, but that cooling to a greater degree in the upper regions permitted the individual crystals in

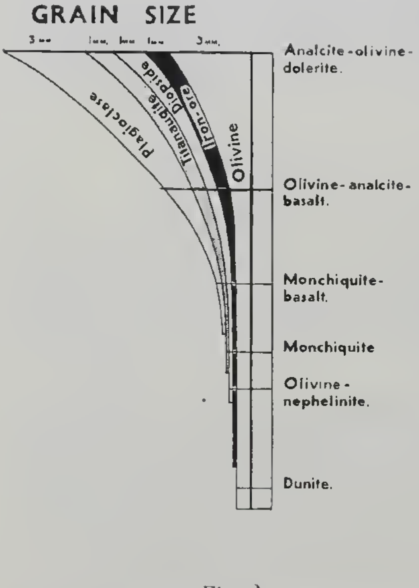

Fig. 2.

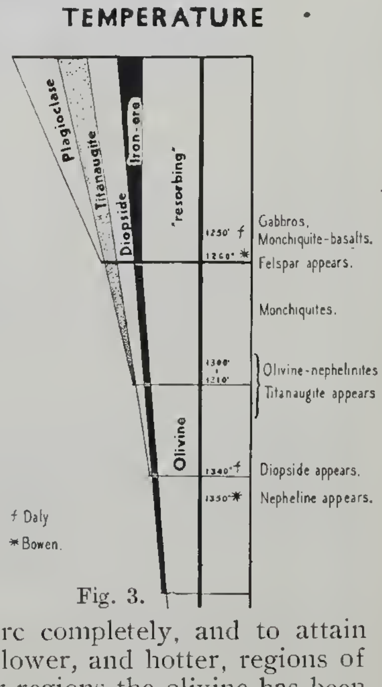

Fig. 3.

the dolerite types to crystallize more completely, and to attain larger dimensions than those in the lower, and hotter, regions of the column. Moreover, in the upper regions the olivine has been actively resorbed, while at the higher temperatures of the "monchiquitic layers" idiomorphic outlines are retained, showing that resorption had not set in. Resorption might be expected to commence with the appearance of diopsidic augite (Bowen, The System: Forsterite-Anorthite-Silica). Actually there seems to be a delay, and the corrosion of olivine is not appreciable until after the plagioclase has commenced to crystallize.

The augite was initiated as a diopsidic material, and had grown to a moderate size in the upper regions before the temperature of the lower part of the column had fallen sufficiently for it to appear there. By the time it was forming in the lower regions, titanaugite was crystallizing in the upper parts, wherever the titania was free to enter the pyroxene molecule. Plagioclase commenced to crystallize soon after the appearance of titanaugite, and the stronger crystallizing force of the former prevented idiomorphic growth of the latter as soon as a crystal mesh was established.

Intrusion apparently occurred just before the augite of the monchiquite layer reached the titanaugite stage, but not before augites had begun to sink towards these layers. Rapid cooling set up numerous diopsidic cores in the fluid magma, and a final rim of titanaugite developed before the consolidation or freezing. Movement into position probably squeezed out much of the residual liquor, concentrating the crystals, but a large portion of the fluid, of felspathic character, congealed as glass. In the slightly cooler "monchiquite-basalt layer," the pre-intrusion cooling had advanced sufficiently for felspar to commence to crystallize in increasing proportion. A factor supporting the view of intrusion in this almost fluid state is the uniform fineness and idiomorphic character of the groundmass crystals in the monchiquitic rocks, as opposed to the variable coarseness of the less basic types.

In the higher parts of the column, where crystallization had proceeded further, gravitational differentiation had been increasingly active, probably about a mean composition of magma represented by the olivine-analcite basalt, resulting in a downward movement of the olivine, and to a lesser extent, of augite. In a few rocks even the plagioclase shows evidence of sinking. The soda content appears to have concentrated locally in the upper region, quite independently of gravitational differentiation, enriching individual dykes, and may have been carried into place by the volatile fluxes, such as the water vapour now associated with it in the analcite. It arrived immediately prior to complete consolidation, enabling a slight reaction with the pyroxene to take place, and producing an intersertal distribution of the incoming material, i.e., the analcification was deuteric.

There might in this manner be some comparison between the differentiation of the rocks forming these dykes and necks, and such bodies as the Garbh Eilean sill of the Shiant Isles (Walker,

1930) ; but while in the latter case there was a floor on which the sinking olivine might concentrate, the lack of floor in the magma chamber here postulated, or its abyssal situation would lead merely to the remelting of the olivine as it sank to depth, and the consequent enrichment of the magma in magnesia and iron. Such clots of olivine as have been found in the monchiquites (p. 11) are to be regarded as remnants of this "potential layer," rather than as evidence of such a layer itself.

The nephelinite, on account of its restricted and isolated occurrence, presents difficulties. The early crystallization of nepheline with diopside indicates that the conditions peculiar to agpaitic differentiation (Backlund, 1932) obtained during the early period of differentiation. In such a system nepheline and orthoclase are among the first minerals to separate, and are forced by their specific gravities to rise in the magma, and concentrate at the top of the magma column. Kranck (1928), in discussing the origin of the abyssal melilite rock, turjaite, showed that the crystallization of nepheline precedes that of orthoclase, the nepheline accompanying diopside, while the appearance of orthoclase was delayed until the aegirine molecule commenced to crystallize strongly. This should lead then to the nepheline concentrating in the uppermost layers, as an urtitic magma, while nepheline and orthoclase in decreasing amount would form the layers beneath.

From the petrographic evidence of the Gippsland suite, olivine commenced to crystallize earlier than did nepheline, and was still crystallizing when the nepheline appeared (see Fig. 2) ; but the olivine of the nephelinite is wholly phenocrystal, and does not appear in the groundmass, so that olivine had ceased to crystallize within the nephelite magma before extrusion caused consolidation. This would suggest that the olivine of this uppermost layer of the magma column was sinking while the nepheline was rising; and that the extrusion of the nephelinite "fixed" the magma in this intermediate stage of differentiation, and left behind a magma enriched in magnesia and somewhat impoverished in soda. Backlund writes (p. 11) :—" . . . . The early and sudden crystallization of felspars and felspathoids, and their strong tendency to rise in the thin but heavy residual fluid, leads to the formation of a film at the top of the advancing channel of the magma chamber in such a manner as to preclude an escape of gas. In consequence of this, pressure (and temperature) in the top film rises . . . . As a result, pronounced rhythms of periodical culminations tend to develop, viz., intrusions at regular intervals. . . . Meanwhile the volatiles accumulate."

The ultimate tendency is to separate the mother liquid into two sheet-like suites—the upper of felsic, and the lower of femic composition, probably grading into one another. It is suggested that the nephelinite represents the upper "sheet" in mid-process of differentiation, and that the felsitic dykes of the area represent the process at the stage when orthoclase is concentrating in the upper region, partial removal of the nepheline leaving the residual magma enriched in silica, which has led to the formation of oligoclase rather than nepheline in the felspar "sheet." The main suite of dykes, spasmodically enriched in analcite by fluxing of the alkalis by the partially retained gases, represent the femic "sheet." It is probable that the analcite-rich dolerites belong, as in the hypothetical column of Fig. 2, to the upper part of this zone, where the gas attack would be concentrated.

Temperatures.

In Fig. 3, an attempt has been made to suggest the temperatures of formation of the various dyke types, and the minerals constituting them. Like Fig. 2, it is based on the assumption of differentiation within a magma chamber.

The temperatures suggested are, at best, wide approximations, since they are based on data for the melting points of single crystals (Daly, 1933) or from suggestively similar points within restricted systems (Bowen, 1923). The effects of fluxing or eutectic crystallization are ignored.

The olivine crystallized out before the iron-ore, but later than the picotite. Daly gives 1,580 deg. C. as the melting point of magnetite, and that of olivine as 1,360 deg.–1,410 deg. C., while forsterite is formed about 1,890 deg. C. It would seem that Daly's figure is low, and that the olivine appeared about 1.580 deg. C.+.

The mineral to crystallize after magnetite appears to have been nepheline (commences to crystallize at 1,350 deg. C., Bowen; melts at 1,370 deg. C., Daly). Following closely, or simultaneous with it, the diopsidic augite appeared. From Bowen's experimental data, this might be expected to coincide with the beginning of the resorption of olivine, at a temperature of about 1,370 deg. C., but actually the resorption is delayed until the appearance of plagioclase, about 1,260 deg. C. (Daly, gabbros commence to crystallize about 1,250 deg. C.; Bowen, 1,260 deg. C.). Daly gives the figures 1,391 deg. C., 1,310 deg. C.–1,370 deg. C., and 1,185 deg. C,–1,200 deg. C. for the melting point of artificial diopside, bronzites, and augites respectively. Here the diopsidic augite crystallizes at or about 1,350 deg. C., and titanaugite between this temperature and 1,250 deg. C., when plagioclase appears, i.e., approximately at 1,300 deg. C.–1,310 deg. C.

Then the olivine-nephelinite should have been extruded at about 1,310 deg. C.–1,350 deg. C., monchiquites at about 1,260 deg. C.–1,310 deg. C., and monchiquite-basalts around 1,250 deg. C. The analcite-olivine-dolerite, despite its ability to form aegirine, has done so to only a very slight degree, the probable prohibitive factor being consolidation. Daly gives the melting point of acmite as 975 deg. C. (natural), and 990 deg. C. (artificial). If aegirine is assumed to melt about this range, the dolerites should have completed solidification between 950 deg. C.–1,000 deg. C., and were probably intruded at a temperature not greatly above 1,100 deg. C. The analcite-basalts, which show little or no sign of aegirine, must have solidified about 1,000 deg. C., and have been intruded at a correspondingly higher temperature, between 1,100 deg. C.–1,200 deg. C. This agrees approximately with the statement of Daly, that the Clee Hill dolerite (England) flows readily when heated to 1,070 deg. C. This rock is of a grain size intermediate between the basalts and the dolerites here described.

The felsitic, or trachyandesitic dykes, contain a little green hornblende, which could not have formed above 750 deg. C. (green hornblende changes to brown at 750 deg. C. or above, Kozu, Yoshiki, and Kani, 1927). Grout suggests a temperature of 550 deg. C. for the formation of such an amphibole, but this seems too low, since the remainder of the rock is entirely felspathic and fine-grained.

Age Relations and Correlations.

The age of these dykes and necks cannot be fixed precisely, but they pre-date the major faulting of South Gippsland, and appear to have been intruded before the previous subsidence period, when the Brown Coals were deposited, which would place them at least as old as Older Basalt (i.e., Lower Oligocene). Their relation to the Older Basalts of this area is not yet known, but isolated slides of the latter have many characters in common with the dykes, which may represent feed channels from which the basalts are now eroded. At Berwick and Aberfeldy large anorthoclase crystals, similar to those of the Moyarra Neck, are found in the basalts. The age of these Older Basalts was regarded formerly as Miocene, but with accumulating evidence as to the age of the younger Brown Coals, they are becoming to be regarded to be at least as old as Lower Oligocene.

The other possibility is that the Older Basalt period closed with a widespread intrusion of dykes about various centres—one in South Gippsland, one about Bendigo, and another south of the Harcourt granitic massif. The dykes of the latter centre intrude the Older Basalts there.

The constancy of the north-west strike throughout all these dyke areas is probably due to the equally constant north-westerly strike of the Palaeozoic basement through which they have all penetrated.

The remarkable similarity to the smallest detail between the monchiquites of Gippsland, and those of Bendigo, Ballarat, Gorong, Greendale, Maldon, and Daylesford, in Central Victoria, is such as to convince the author that they must have had a closely similar origin, despite the absence of crinanites from the latter areas. They show early segregation of olivine, with widespread serpentinization of that mineral, and an inclusion in one Bendigo dyke points to the existence of a gabbro body at depth. The associated dykes are camptonites, olivine-basalts, and some olivine-dolerites, while at Greendale there is the olivine-nephelinite referred to in this paper (p. 115). It seems apparent that in these areas the gravity differentiation has acted alone, and that late-stage analcitization did not develop.

The north-west dykes of Colonsay (Mem. G. S. Scott, 1908, 1911), consisting of crinanites, olivine-dolerites, a minor number of monchiquites, and occasional nepheline-bearing monchiquites, present a close parallel to the Gippsland association, both in the types developed, and their relative quantities. In composition, however, the Gippsland "crinanites" are nearer to the Palaeozoic crinanites of Scotland (Tyrrell, 1923, 1928), in that they have a high potash content. They differ from both of these groups in their low titania content. The picrite-crinanite sill of the Shiant Isles (Walker, 1930) provides a further parallel association, if the individual types of dyke are regarded as representing, in step form, the gradation there produced by gravity differentiation. There again, the analcitization has been independent of the differentiation, and developed at a late stage (Daly, 1933, p. 398).

Conclusions.

A suite of dykes, with a prevalent north-westerly strike, was intruded into the Jurassic sediments of South Gippsland in Lower Oligocene time. The suite comprises trachyandesites, analcite-olivine-dolerites, olivine-analcite-basalts, monchiquite-basalts, monchiquites, and possibly olivine-nephelinites. When arranged in this order of increasing basicity, they exhibit chemical and petrological gradation into the adjacent types, and are considered to have been derived from a common magma, of a composition about that of the olivine-analcite basalt, mainly by gravity differentiation, initiating under agpaitic conditions. The analcitization, however, developed independently, and locally, at a late pre-consolidation stage, by volatile fluxing, the fluxing agent being probably water vapour. The fluxing action on the alkalis was selective in favour of the soda, possibly because potash does not so readily enter into solution or combination with water vapour.

The rocks may post-date, but are probably genetically related to the Older Basalt Series. The very similar monchiquite dykes of Central Victoria are considered to be contemporaneous with the Gippsland dykes, and to have had a similar origin, but in that area the analcitization has not been developed.

References.

1876.—R. A. F. Murray. Report on the Geology and Mineral Resources of South-west Gippsland. *Progress Rept. Geol. Surv. Vic.*

1892.—J. Stirling. Special Report on Victorian Coalfields. *Geol. Surv. Vic.*

1903.—A. E. Kitson. Volcanic Necks at Anderson's Inlet. *Proc. Roy. Soc. Vic.* (n.s.), xvi.

1908.—*Memoir No.* 35, *Geol. Surv. Scotland.* The Geology of Colonsay and Oronsay, with part of Ross.

1909.—W. H. Ferguson. Report on the Lower Powlett, Cape Paterson, and Inverloch Quarter Sheets. *Memoir No.* 8, *Geol. Surv. Vic.*

1911.—*Memoir No.* 45, *Geol. Surv. Scotland.* The Geology of Knapdale and Jura.

1912.—F. Stillwell. Notes on the Monchiquite Dykes of Bendigo. *Proc. Roy. Soc. Vic.* (n.s.), xxv.

1917.—A. E. Kitson. The Jumbunna and Powlett Plains District, South Gippsland. *Bulletin No.* 40, *Geol. Surv. Vic.*

Annual Report for the Secretary for Mines, Victoria, for the year 1917.

1923.—N. L. Bowen. The Evolution of Igneous Rocks.

G. W. Tyrrell. Classification and Age of the Analcite-bearing Igneous Rocks of Scotland. *Geol. Mag.*. lx., p. 249.

1927.—Kozu, Yoshiki, and Kani. *Sci. Rept., Tohoku Imp. Univ.*. *Ser.* III, iii., pp. 143–159.

1928.—G. W. Tyrrell. The Geology of Arran. Geol. Surv. Scotland.

D. J. Mahony. Some Tertiary Volcanic Minerals *Proc. Roy. Soc. Vic.* (n.s.), xl., (2), p. 62

E. H. Kranck. On Turjaite and the Ijolite Stem of Turja, Kola. Diss. Helsingfors. (Also Backlund, 1932, p. 10.)

1930.—F. Walker. The Geology of the Shiant Isles. *Quart. Journ. Geol. Soc.*, lxxxvi., p. 355.

1931.—D. J. Mahony. Alkaline Tertiary Rocks near Trentham and Drouin, Victoria. *Proc. Roy. Soc. Vic.* (n.s.), xliii., (2), p. 123.

1932.—H. G. Backlund. On the mode of Intrusion of Deep-seated Alkaline Bodies. *Bull. Geol. Instit. Upsala,* xxiv.

1933.—R. A Daly. The Igneous Rocks and the Depths of the Earth, p. 65.


New South Wales
Victorian Highlands
VICTORIA
(Locality Reference)
GEOLOGICAL SKETCH MAP
OF
SOUTH GIPPSLAND
0 2 4 6 8
MILES
REFERENCE
Silurian
Granite (Devonian)
Jurassic (Coal-bearing)
Basalt (Eocene)
Tertiary (Mainly post-basalt)
Recent
Dolerite Dykes
Monchiquite Plugs
Nepheline
Faults
Compiled from the maps of the Geological Survey of Victoria. (Ann. Rept. Sec. Mines 1917).
YARRAGON
TRARAL
YANNATH
POOWONG
JEETHO
KORUMBURRA
JUMBUNNA
JUMBUK
GUNYAN GUNYAR
BINGINWARRI
YARRAN
TOORA
DOOMBURRIM
WONTHAGGI
TARWIN
Cape Paterson
CORNER INLET
SNAKE ISLAND